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Use of offshore wind farms to increase seismic resilience of Nuclear Power Plants

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ABSTRACT:

One of the challenges faced by the engineering profession is to meet the energy requirement of an increasingly prosperous world. Nuclear power was considered as a reliable option until the Fukushima Daiichi Nuclear Power Plant (NPP) disaster which eroded the public confidence. This short paper shows that offshore wind turbines (due to its shape and form, i.e. heavy rotating mass resting at the top of a tall tower) have long natural vibration periods (>3.0 s) and are less susceptible to earthquake dynamics. The performance of near-shore wind turbines structures during the 2011 Tohoku earthquake is reviewed. It has been observed that they performed well. As NPPs are often sited close to the sea, it is proposed that a small wind farm capable of supplying emergency backup power along with a NPP can be a better safety system (robust and resilient system) in avoiding cascading failures and catastrophic consequences.

Keywords: Offshore Wind Turbines, Nuclear Power Plant, Fukushima Nuclear Power Plant, 2011 Tohoku Earthquake

INTRODUCTION

The world population is predicted to increase from 6 to 8 billion (i.e. 33% rise) between 2000 and 2020. Accordingly, the demand for energy is set to increase by about 60% (IAEA 2002). While renewable energy sources, such as offshore marine sources (wind, wave, and tidal), onshore wind, and solar, are expanding, nuclear power is perceived to cover a significant proportion of the baseload supply. The advantage of nuclear energy is low CO2 emission and has a proven track record to deliver reliable power in most countries. The safety philosophy is critical for designing such structures especially in seismic zones (Bommer 2010). A dramatic change of the public risk perception towards nuclear energy has happened in the aftermath of the 2011 Tohoku earthquake due to the Fukushima Nuclear Power Plant (NPP) disaster. Further details of the 2011 Tohoku earthquake can be found in Bhattacharya et al. (2011) and Goda et al. (2013). In this context, it is noteworthy that India and China, which are situated in seismically active regions, are constructing NPPs to meet the increasing high energy demand.

The scope of the article is to review the effects of 2011 Tohoku earthquake on two energy systems (Fukushima Daiichi NPP and near-shore offshore wind farms) operating at that time to see if any lessons can be learnt to make the NPP safety system more robust and resilient.

SAFETY SYSTEMS OF NUCLEAR POWER PLANTS (NPP)

According to the nuclear safety philosophy, buildings within a NPP are divided into safety-related and non-safety related. Safety-related building structures include reactor building, auxiliary systems building, switchgear building, emergency backup generator building, or the vent stack building. The pressure vessels (for example pre-stressed concrete) of gas-cooled reactors and the containment buildings of PWR (Pressurised Water Reactor) and BWR (Boiling Water Reactor) are the key safety related structures. In certain design, such as BWR, the turbine building is also classified as safety-related, as radioactive live steam is fed directly into the turbine. In particular, the reactor is a critical component and the safety barrier systems consist of: (a) fuel pellets; (b) fuel rod cladding; (c) reactor pressure vessel; (d) reinforced concrete cylinder as radiation shield often known as biological shield; (e) containment; and (f) reinforced concrete shell. On the other hand, non-safety related building structures typically include administrative and workshop buildings, gatehouse, and cooling towers.

For the purpose of safety evaluation, IAEA (2002) safety standards recommend that seismic input level should be considered for SL-2 (Seismic Level 2) which corresponds to an infrequent earthquake with a return period of 10,000 years (10^{-4} per year). This is considered by plant developers as a bottom-line event, i.e. the most onerous event for which the bottom-line plant provides protection. Apart from SL-2, the IAEA also recommends for SL-1 (Seismic Level 1) which corresponds to less severe and more frequent earthquakes with a probability of 10^{-2} per year being exceeded.

The safety philosophy in NPPs is highly redundant and essentially designed for the following three main scenarios: (a) control reactivity of the nuclear fuel, safe shut-down and reactor trip and post-trip cooling; (b) cooling fuel assemblies; and (c) controlling radioactive substances and radiation from release to the atmosphere. The safety systems are designed for internal incidents (for example, internal flooding or loss of coolant) as well as external actions (for example, floods, earthquake, and tsunamis). To meet these safety goals, different types of active and passive safety barriers and systems are adopted where the guiding safety principles are redundancy, diversity and spatial separation. Redundancy allows the main safety systems to be replicated so that if one of the systems fails, another can take over. This corresponds to at least two lines of protection for design load case of SL-1 and at least one line of protection for SL-2. Through the diversity principle, major components of the main safety systems are made to different designs so that they don't fail at the same time due to a common cause or same reason. Finally, spatial separation ensures that major components of the redundant safety systems are spaced or located in such a way that if an incident occurs, it has no impact on the other identical redundant modules and that these modules can take over the safety function.

It is of interest to review the Fukushima Daiichi NPP disaster in the light of above safety concepts.

FUKUSHIMA DAIICHI DISASTER

The Fukushima Daiichi NPP consists of six BWR units in the plant and was constructed in 1970s. The working principle is as follows: heat is generated by nuclear fission which transforms water into steam driving a turbine to generate electricity. The critical safety aspect of the whole system is avoiding the melting of the reactor and leaking of radioactive materials to the atmosphere. In this regard, one of the important safety aspects is the cooling system and during the earthquake, there was a loss of external power supply due to the combined events of ground shaking and tsunami.

The earthquake and its triggered hazards (i.e. tsunami and landslide) initiated the crisis of the Fukushima Daiichi NPP. The tsunami, which arrived around 50 minutes following the mainshock, was about 14m high which overwhelmed the 6m high sea walls and resulted in flooding the emergency generator rooms causing the power failure of reactor cooling systems. The loss of the cooling systems led to reactor heating up and subsequent meltdown; consequently, harmful radioactive materials were released to the environment. The power failure also meant that many of the safety control systems were not operational. The release of radioactive materials caused a large scale evacuation of over 300,000 people near the plant and the clean-up costs are estimated to be in the order of hundreds of billions of dollars.

The events leading to the triple meltdown can be described as follows:

(a) During the 2011 Tohoku earthquake, the switching station for Reactors 1 and 2 was damaged by the shaking, whereas the transmission tower that connects the regional substation and Reactors 5 and 6 collapsed due to a landslide (note: Reactors 5 and 6 did not experience the complete loss of power because emergency generators were functional).

(b) Additionally, after 14+m tsunami (M_w9.0 event) arrived at the plant, whereas the sea walls were only 6.5m high (designed based on a M_w8.2 event). As a result, Reactors 1-4 were inundated by the tsunami and lost the emergency diesel generators, DC batteries, and sea-water pumping systems, which were located at the basement of the reactor buildings.

(c) Power supply was lost which was critical for pumping cooling water and as a result Reactors 1-3 experienced meltdown.

PERFORMANCE OF NEAR-SHORE WIND FARM DURING THE 2011 TOHOKU EARTHQUAKE

Figure 1 shows the location of the earthquake and the operating wind farms in the Kanto and Tohoku regions of Japan. The earthquake and the associated effects, such as liquefaction and tsunami, caused great economic loss, loss of life and tremendous damage to structures and national infrastructures (Goda et al. 2013), but very little damage to the wind farms. Figure 2 shows photographs of a wind farm at Kamisu (Hasaki) after the earthquake. Immediately after the earthquake, the wind turbines were automatically shut down (like all escalators or lifts), and following an inspection they were restarted. Figure 3 shows the collapse of pile-supported building at Onagawa. At many locations (e.g. Natori, Ofunato and Onagawa), tsunami heights exceeded 10m, and sea walls and other coastal defence systems failed to prevent the disaster (Fraser et al. 2013).

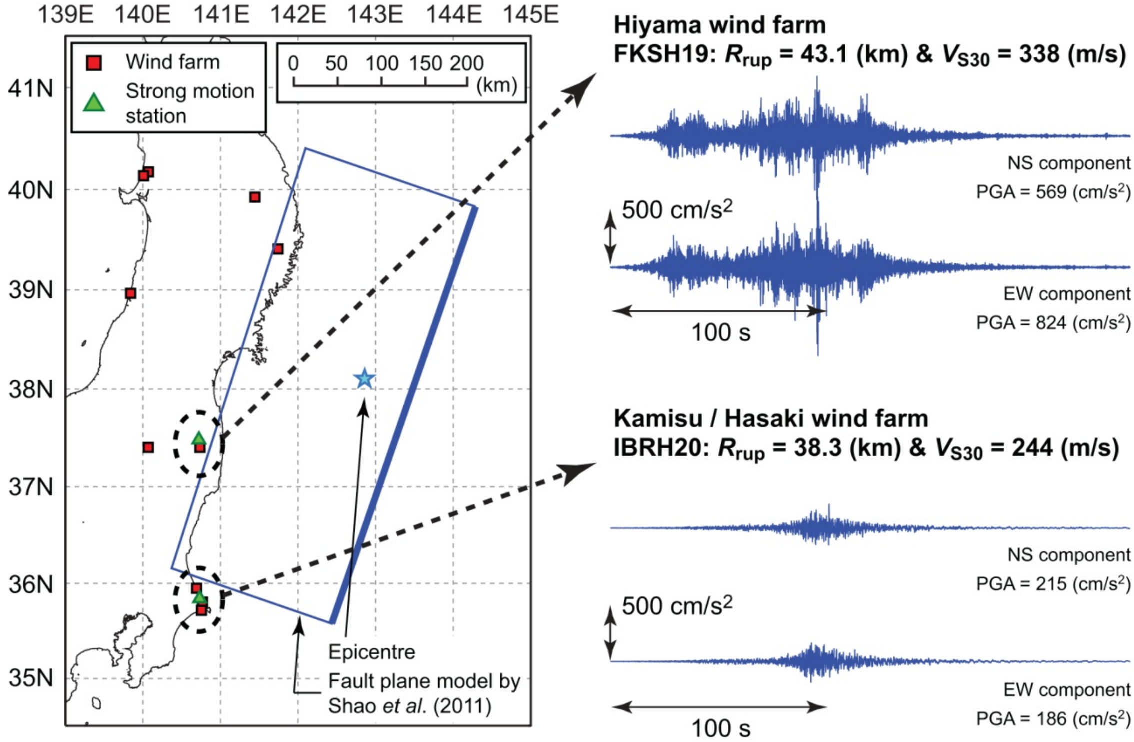

Figure 1: Details of the 2011 Tohoku earthquake and locations of the wind farms

Figure 2: Photograph of the Kamisu (Hasaki) wind farm following the 2011 Tohoku earthquake

Figure 3: Collapse of a pile-supported building in Onagawa

Recorded ground acceleration time-series data in two directions [North-South(NS) and East-West (EW)] near Kamisu and Hiyama wind farms (FKSH 19 and IBRH20) are presented in Figure 1. The observed peak ground accelerations near Hiyama were large, exceeding 0.6g. Figure 4 shows the response spectra of the recorded ground motions at FKSH 19 and IBRH20. The dominant period ranges of the recorded ground motions near the wind farm sites were less than 1.0 second. Importantly, natural vibration periods of offshore wind turbine systems are in the range of 3.0 seconds, significantly longer than the dominant spectral content of the recorded ground motions. Due to non-overlapping, these structures will not get tuned and as a result they are relatively insensitive to earthquake shaking. Nevertheless, earthquake-induced effects, such as liquefaction, may cause some damages to their foundations.

Figure 5 shows a structural/mechanical model of an offshore wind turbine structure where the foundation is represented by three springs: lateral K_L, rotational K_R, and cross K_{LR} stiffness. The tower can be idealised by equivalent bending stiffness and mass per length and can be modelled using two beam theories of Euler-Bernoulli and Timoshenko. Timoshenko beam theory accounts for shear deformation and the effect of rotational inertia and the nacelle-rotor assembly is modelled as a top head mass with mass moment of inertia. Due to the rigidity of the foundation when compared to the tower, the resonant vibration period is very close to fixed-base vibration period (Arany et al. 2015). Other aspects related to dynamic soil-structure interaction of the system can be found in Bhattacharya and Adhikari (2011) and Bhattacharya (2014).

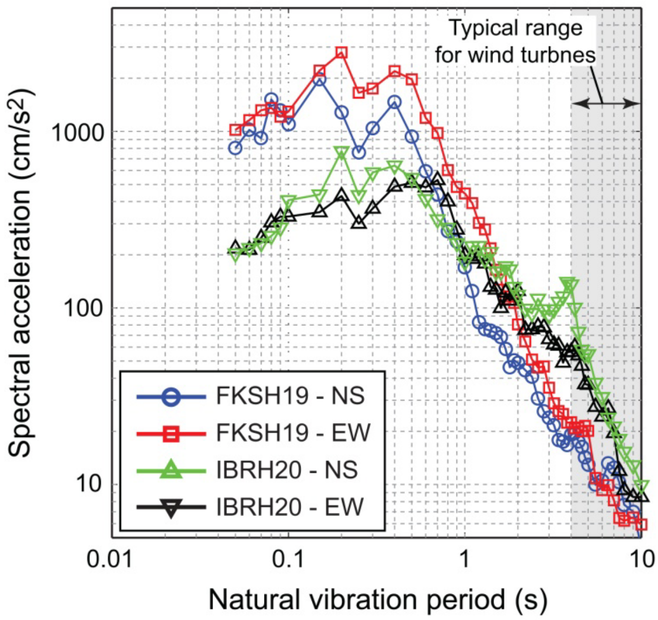

Figure 4: Response spectra of the earthquake and natural vibration period of wind turbines

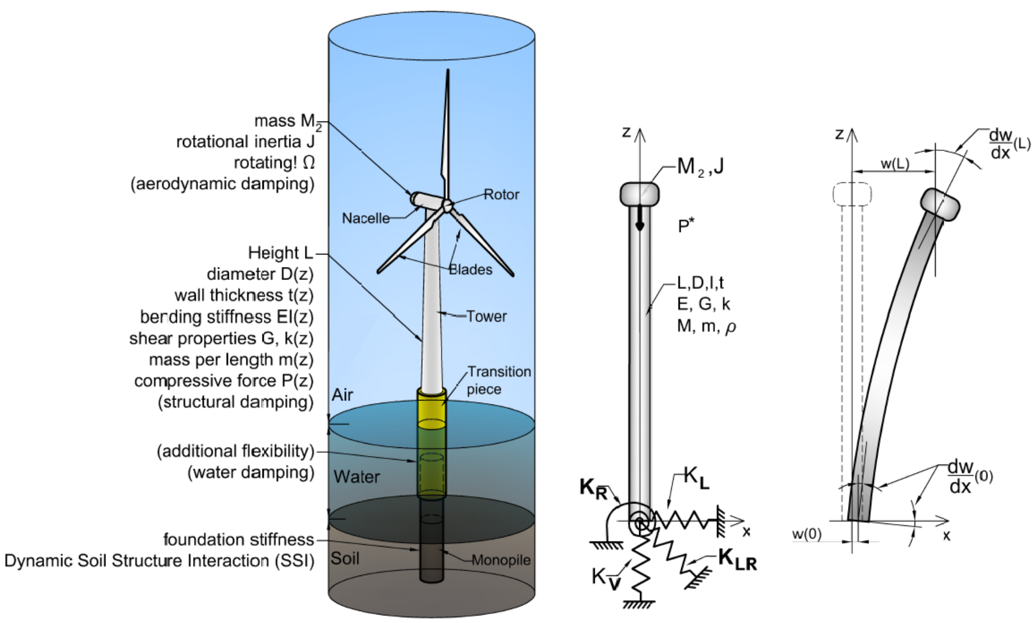

Figure 5: Mechanical model of a wind turbine

DISCUSSION

One may argue, had there been a few offshore wind turbines operating at the Fukushima Daiichi NPP, the crisis may have been averted or the scale of the disaster could have been reduced. The wind turbines, by supplying power to the emergency cooling systems, could have prevented the reactor meltdown. In this context, it is interesting to note that there are plans to replace the Fukushima Daiichi NPP by a floating wind farm (Fukushima Forward 2015), where 2MW semi-sub floating turbine is under operation. Another 7MW oil-pressure-drive type wind turbine on a three-column semi-sub floater has also recently been tested.

A NPP installation is complex structure where one structure is inside another structure and they are structurally connected. During an earthquake, various components interact dynamically and the connecting parts are vital to maintain the integrity and safety of the whole installation. Analysis of the whole system therefore requires an integrated structural analysis not only for the static forces (mainly dead loads) but also for thermal and gas pressure actions together with the dynamic actions due to the earthquakes. In the case of the Fukushima Daiichi NPP, post-earthquake analysis showed that BWRs themselves did not significantly contribute to the accident. Triggered by the earthquake and as per design, the control rods of the BWR reactor were automatically inserted by the hydraulic pressure from underneath the pressure vessel despite the fact that the seismic acceleration were beyond the design basis earthquake. However, the accident was due to prolonged loss of electrical power with almost no instrumentation and control system to secure the safety of the six reactors and six nuclear fuel ponds, a common fuel pools, and dry cask storage facilities. Coatsworth (2011) suggested that the accident had shown the need for mobile power. Therefore, by comparing two energy systems (one very operationally complex and vulnerable to earthquakes and the other is resilient to earthquakes), it appears that the combination of the two can achieve robustness of the complex future energy system.

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